3D-Printed Bridge Project
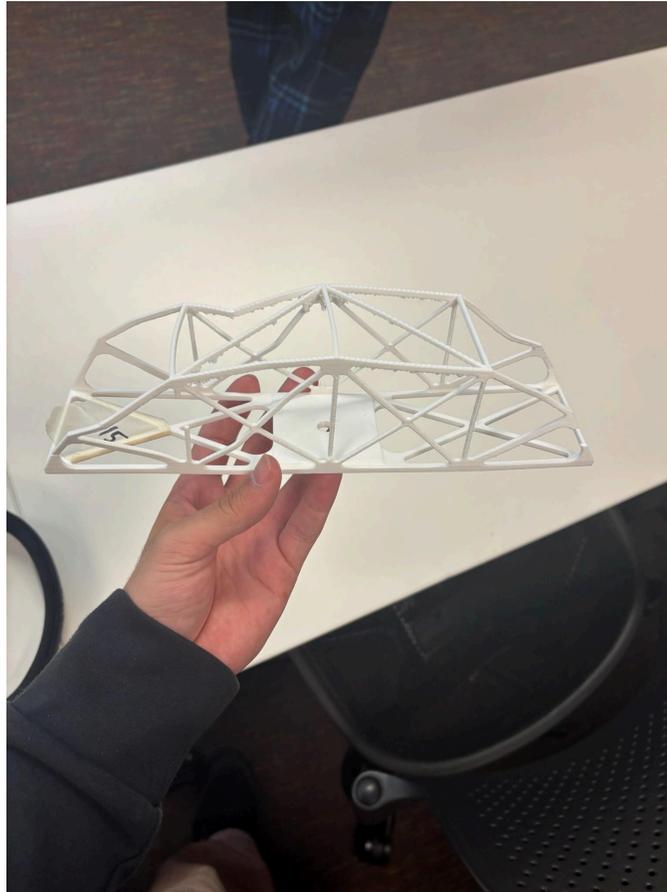

Figure 1. Test Bridge after stress trial

Date of Competition:
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Goal of "3D-Printed Bridge" Project

The project goal was to design, construct, and test a 3D-printed bridge made from PLA (Polylactic Acid) that could hold the largest weight out of all bridges before failure. This project was designed to as closely as practical simulate a real bridge. The bridge would be tested across a 9" span by a central load applied by a 1.75" by 1.75" steel plate attached by a ¼" diameter eye bolt while suspended by two 1" diameter steel half-rounds (Shown Below).
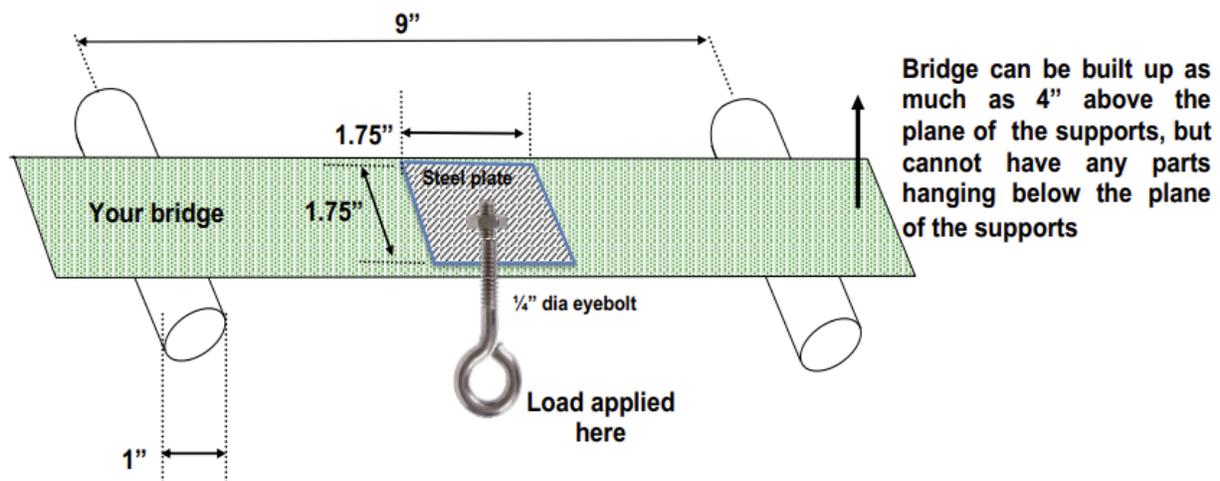

Figure 2. Bridge test device diagram

The bridge specifications to mimic reality are as follows:
- All bridges will be single-print PLA and produced by the BHE lab.
- Bridges must be under 50 grams, but bridges over 40 grams will be penalized according to the following formula
  - Weight (official) = Weight (actual) x (40 g / Bridge weight)2
- The maximum length is 9.75" and the maximum width is 2.5"
- The minimum feature size is 2mm in all directions with 100% fill
- The bridge must have a 2" by 2" opening no more than 4mm above the bottom of the bridge
- The bridge may not go below the plane of the supports.
- The bridge must be less than 4" tall.
- The bridge must be wider than the load plate and have a 5/16" hole for the eye bolt to fit through.

Each bridge needed to comply with the specifications and would be tested by the bridge breaking device. The device would apply a gradually increasing force until the bridge failed, and then the maximum load held would be recorded. These maximum loads would then be compared to the other groups. The group with the greatest maximum load would ultimately be the winner of the project.

Bridge Design Concepts

Design 1
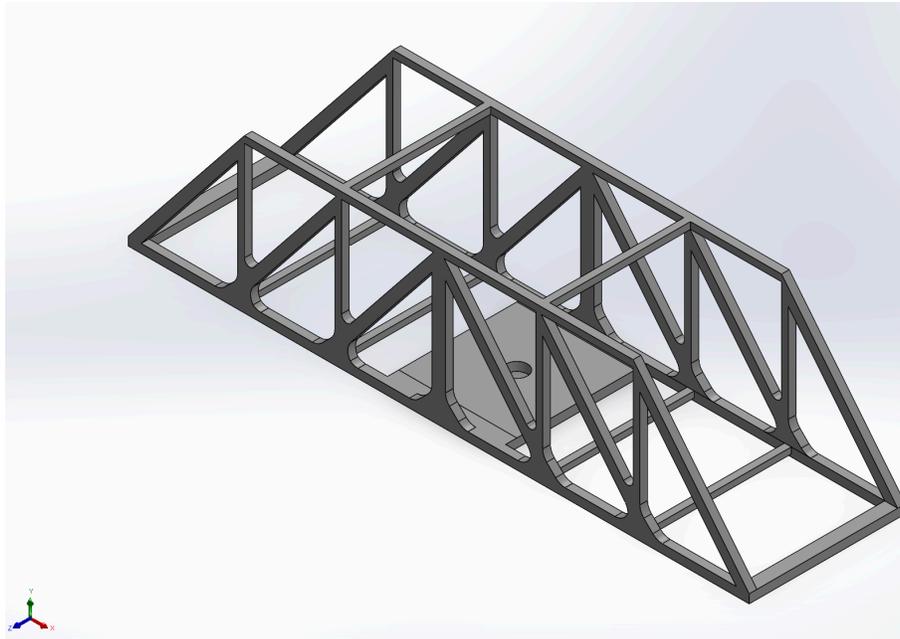
Figure 3. Our first model–a Howe Truss
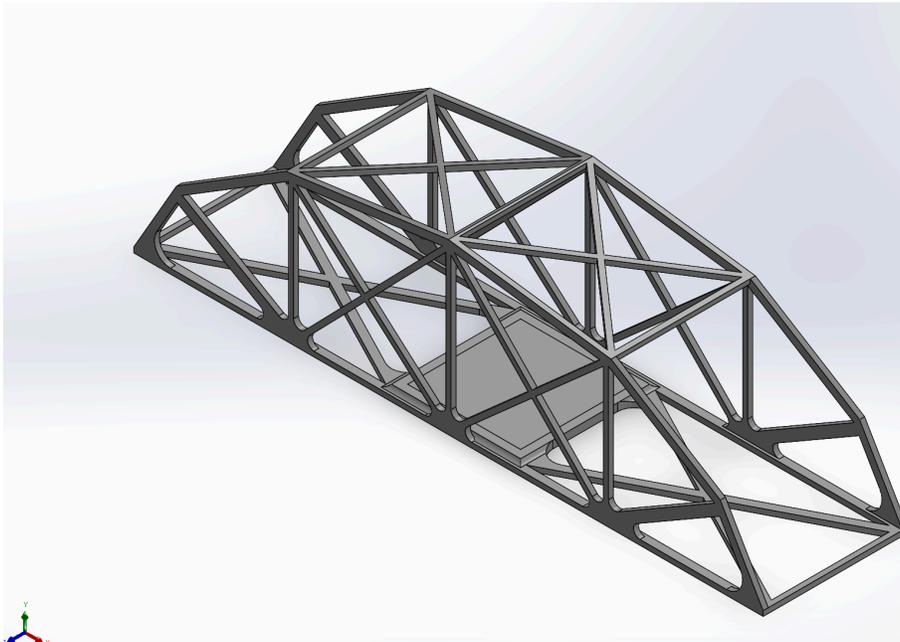
Design 2

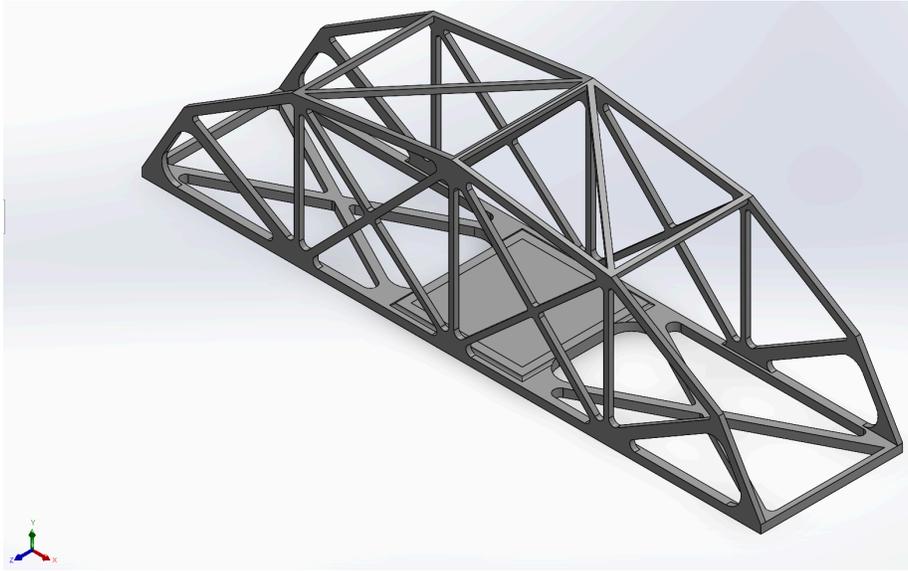**Figure 4.** Our second model–Camelback Truss

Design 3

Figure 5. Our third model–an improved Camelback Truss used for preliminary physical testing
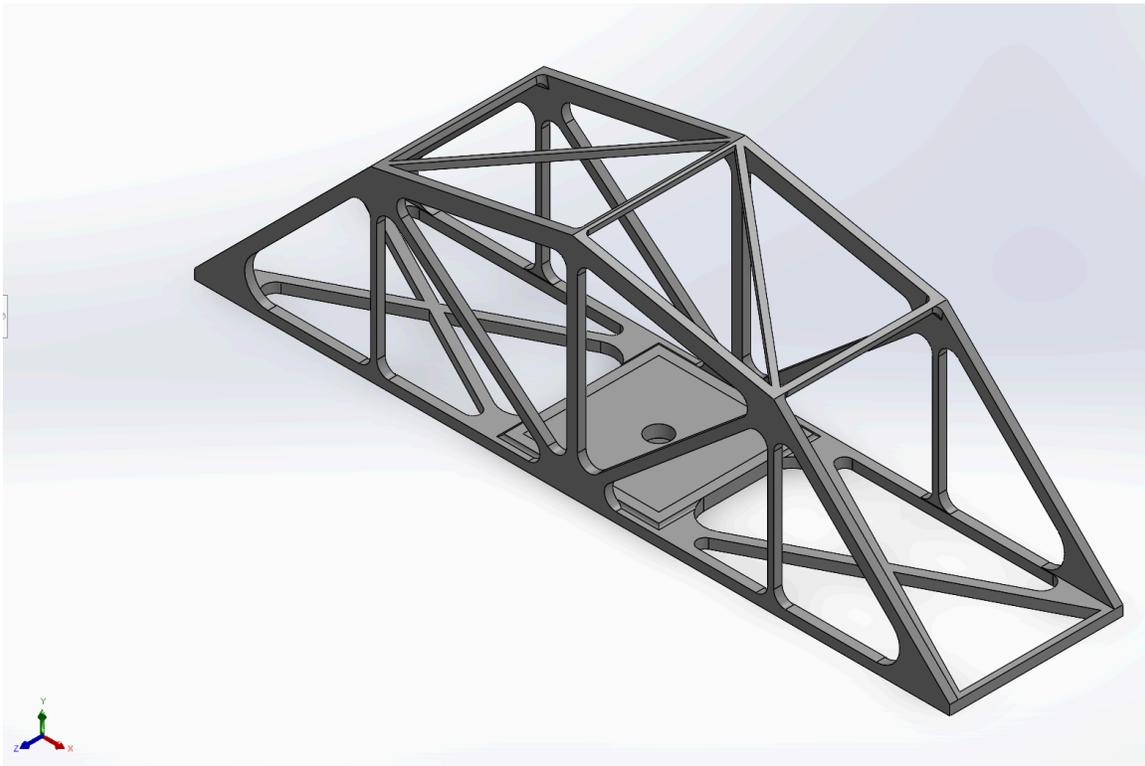
Design 4

Figure 6. Our fourth model- a Camelback Truss with fewer but thicker support beams and one less section on each side
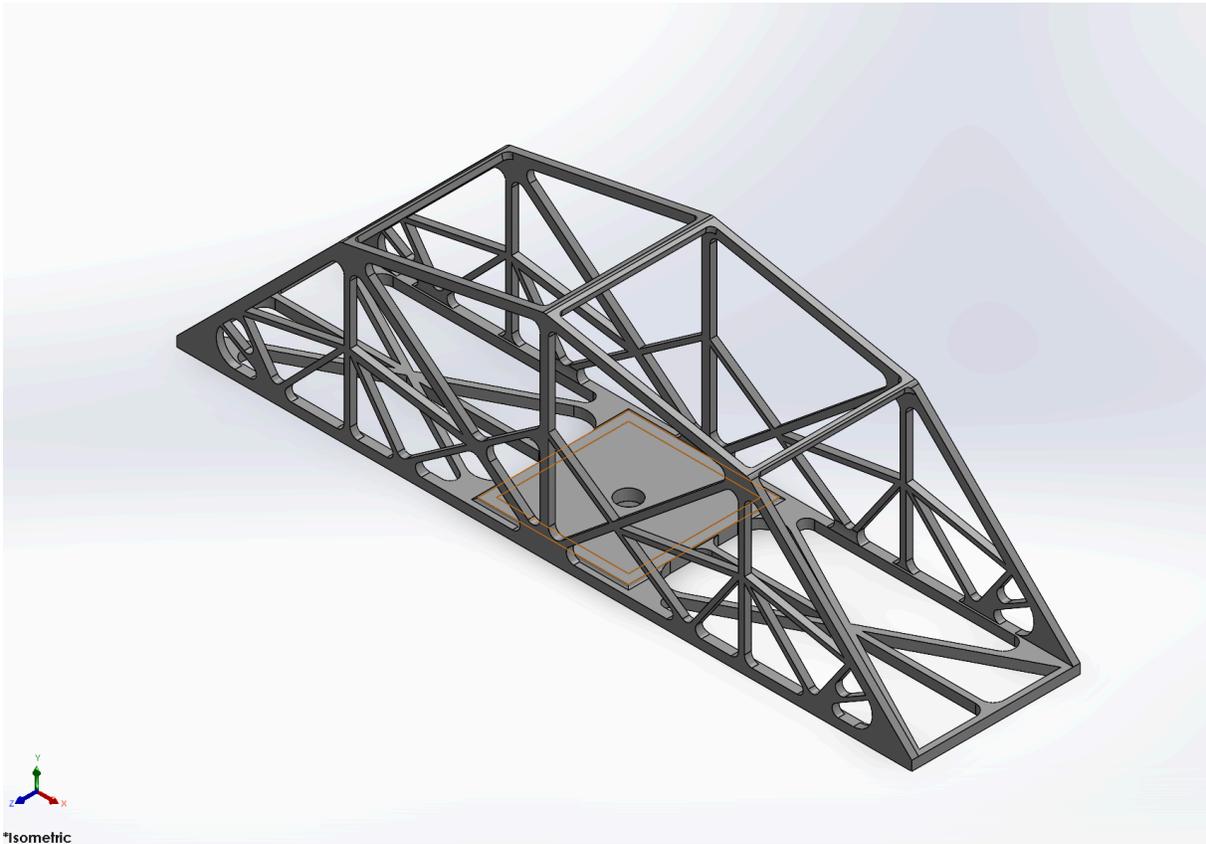
Design 5

Figure 7. Our final model with increased support beams

Testing Design Concepts

I. Methods

To evaluate our bridge designs, we used Solidworks for modeling and conducted Finite Element Analysis (FEA) on each design iteration in order to determine the best choice. The data table of properties for the Finite Element Analysis will be displayed under "study properties" for each design.

We modeled bridges according to project specifications, creating five design variations. Split lines, each 0.1" wide, were defined as the roller and fixed joints, set 9" apart, 4.5" from the center (Table 3). Furthermore, a 1.75 in² square split line was used in the center of the bridge to apply a 50N load to each bridge (Table 2). While the 0.25" diameter eyebolt hole is included in our designs, we opted not to include them in simulations due to the recommendations of laboratory TAs as it would more accurately show failure points. We refined the design based on the FEA results, reinforcing areas showing high stress and reducing material in low-stress regions. Important specifications, like mass, will be included in "part properties" underneath each part, and the resulting data will be shown under "Stress results" and "Displacement Results."

We defined a custom plastic with the average tested properties of our PLA in the z-direction (Table 1). We chose to use the properties in the z-direction because the yield strength and elastic modulus are lower in this orientation, and since the load is applied along the z-axis, failure is most likely to occur in this direction.

Material Properties:

Yield Strength (MPa)	10.83
Elastic Modulus (MPa)	161.24
Density (g/cm³)	1.25

Table 1. The Yield Strength, Elastic Modulus, and density input into the custom plastic in Solidworks are used for all tests.

Load and Constraint Information

Load set

Load Set Name	Load 1
Load Type	Force
Number of Load Elements	1
Load Value	50N

Table 2. The load applied in all simulations. The load is distributed over a 1.75" x 1.75" area.

Constraints

Number of Constraints	2
Number of Fixed Geometry Constraints	1
Number of Roller Constraints	1

Table 3. The constraints used on every simulation.

Design #1

1. Introduction

This truss bridge was modeled after a Howe truss, which is a common bridge truss. It was chosen due to its simple design, and its effectiveness when only vertical loads are applied. We thought that this established truss would provide good rigidity and load distribution and provide us with a good starting point. (SkyCiv Engineering)

2. Part Properties

Part Name	Design 1
Mass (g)	39.22
Adjusted Mass (g)	36.47
Volume (in³)	1.91
Surface area (in²)	52.48

Table 4. The part properties of our first design. The adjusted mass factors in the conversion factor between our expected mass and actual mass (0.93). This conversion factor will be explained further in Design 3.

3. Study Properties

Mesh Density	Fine
Jacobian Points	16 Points
Degrees of Freedom	250,041
Number of Nodes	83,670
Number of Elements	43,328
Solve Type	Iterative

Table 5. The properties used to perform the study.

4. Stress Results

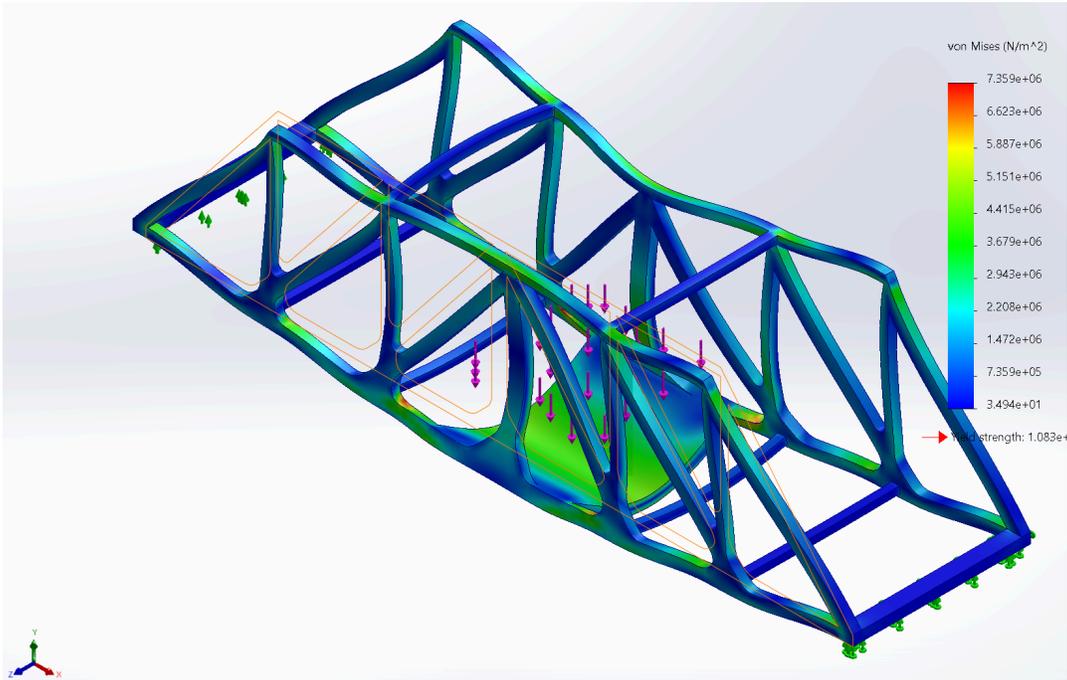| Max Von Mises Stresses (N/m²)	7.359e+06
Yield Strength (N/m²)	1.083e+07
Location of Max Von Mises	On the base connected to the centermost diagonals.
Factor of Safety at 50N load	1.472

Table 6. Displays the Stress results of our first design.

Figure 8. The stress contour plot for our first design

5. Displacement Results

Maximum Displacement (mm)	10.86

Table 7. Displays the displacement results of our first design.
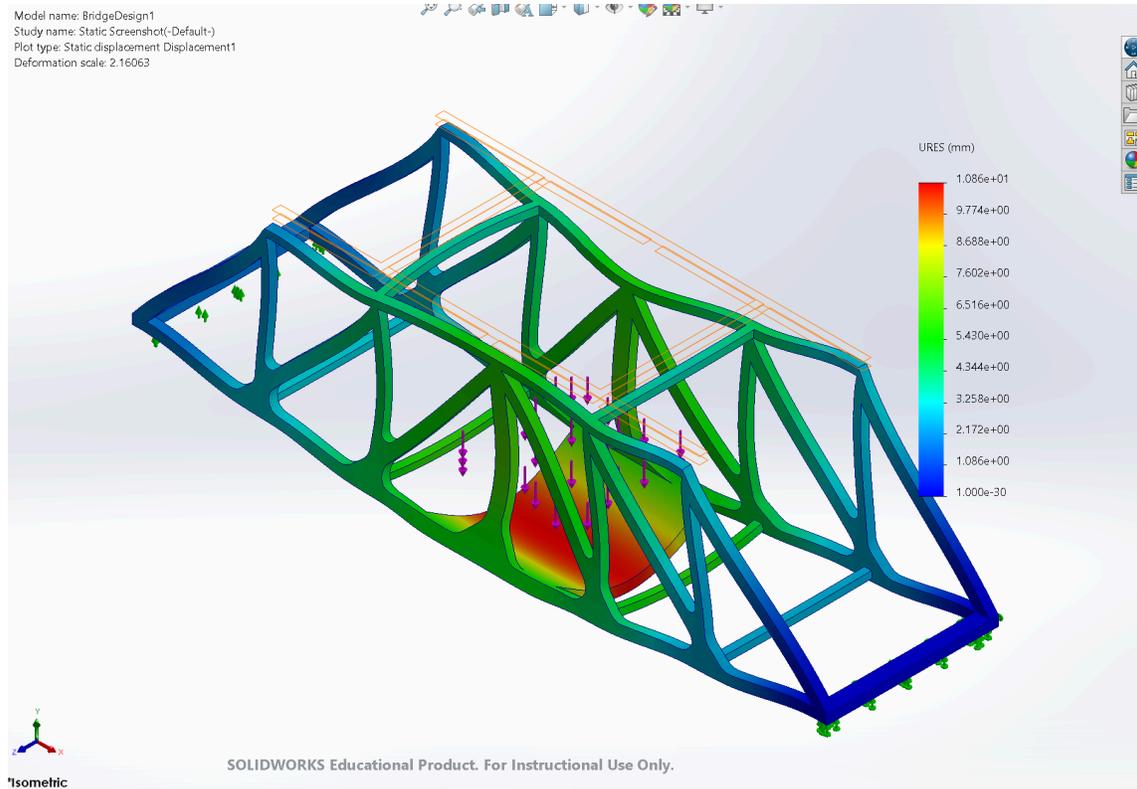
Figure 9. The displacement contour plot for our first design.

Design #2

1. Introduction

The goal of this design was to create an arch bridge. Arch bridges are effective at transferring compression forces downward, giving them a high load-bearing capacity (Shirley-Smith and Billington). The cross bracing on the base and the ceiling should provide extra support to regions around where the load is applied, regions where we saw large displacement and high stress.

2. Part Properties

Part Name	Design 2
Mass (g)	31.59
Volume (in^3)	1.54
Surface area (in^2)	54.05

Table 8. The part properties of our second design. It is significantly under the 40g mass.

3. Study Properties

Mesh Density	Fine
Jacobian Points	16 Points
Degrees of Freedom	214,584
Number of Nodes	71,608
Number of elements	20,199
Solve Type	Iterative

Table 9. The study properties of our second design were used to solve for FEA.

4. Stress Results

Max Von Mises Stresses (N/m^2)	1.325e+07
Yield Strength (N/m^2)	1.083e+07
Location of Max Von Mises	At the bottom of the outermost part of the arch.
Factor of Safety at 50N load	N/A (Past Failure)

Table 10. The stress results of our second iteration under a 50N load. This bridge failed under the described conditions.
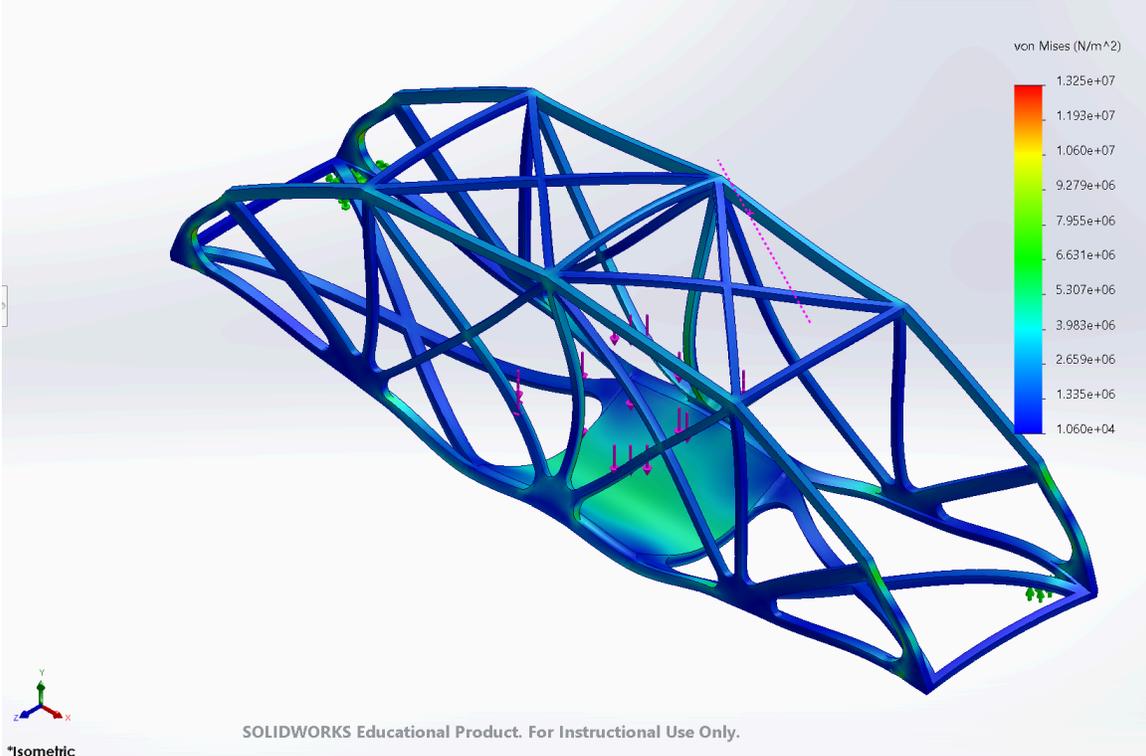
Figure 10. The stress contour plot. This bridge reached failure underneath the outermost part of the arch.

5. Displacement Results

Maximum Displacement (mm)	8.769

Table 11. The displacement results. We noted the reduced displacement.

Model name: BridgeForBob
Study name: Static Screenshot(-Default-)
Plot type: Static displacement Displacement1
Deformation scale: 2.82647

URES (mm)

8.769e+00
7.893e+00
7.016e+00
6.139e+00
5.262e+00
4.385e+00
3.508e+00
2.631e+00
1.754e+00
8.769e-01
1.000e-30

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*Isometric

Figure 11. The displacement contour plot. We noted how the displacement was concentrated on the center plate.

Design #3

1. Introduction

The goal of this bridge was to improve upon our second design by strengthening its weaknesses. Since we saw minimal stress on the bridge's roof, we removed one of the cross beams, and we strengthened other areas by thickening the beams and adding fillets to all sharp edges.
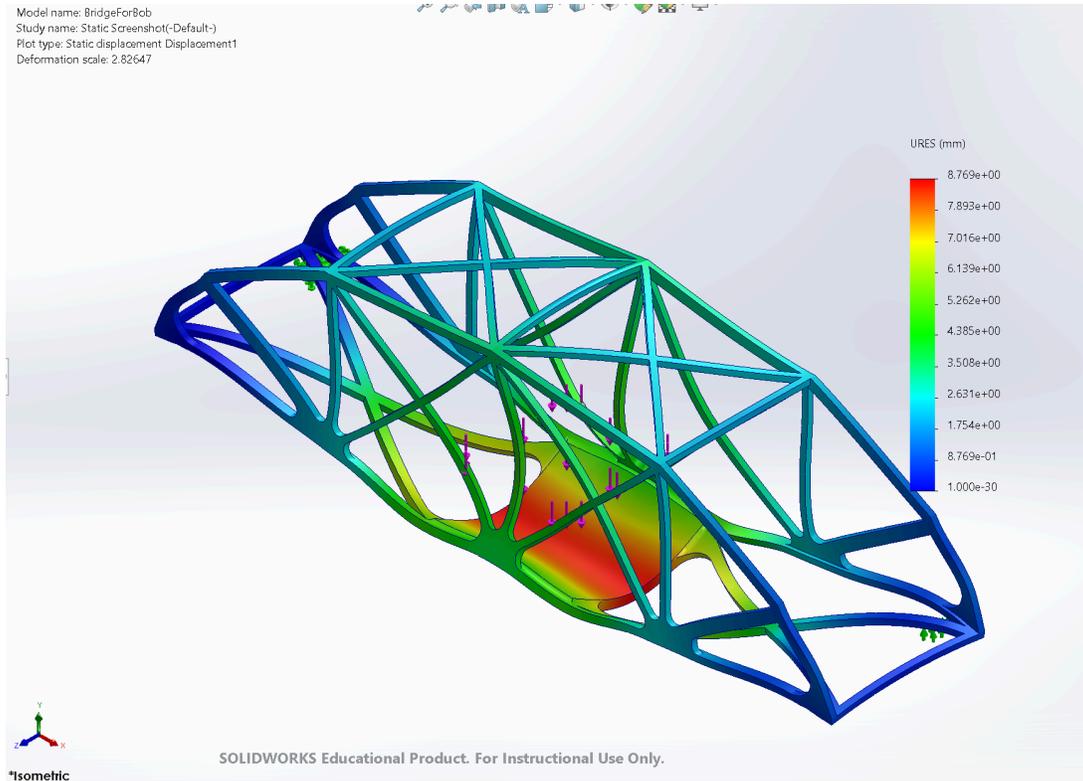
2. Part Properties

Part Name	Design 3
Mass (g)	40.00
Adjusted Mass (g)	37.2
Volume (in^3)	1.95
Surface area (in^2)	56.38

Table 12. The part properties of our third design. The (unadjusted) mass is exactly at the 40g limit.

3. Study Properties

Mesh Density	Fine
Jacobian Points	16 Points
Degrees of Freedom	125,664
Number of Nodes	41,490
Number of Elements	20,297
Solve Type	Intel Sparse

Table 13. The study properties of design 3. Solidworks used Intel Sparse as the solver instead of Iterative.

4. Stress Results

Max Von Mises Stresses (N/m^2)	7.783e+06
Yield Strength (N/m^2)	1.083e+07
Location of Max Von Mises	Above the fillet on the outermost edge when the arch begins
Factor of Safety at 50N load	1.391

Table 14. The stress results of our first test. The Von Mises stresses are slightly higher than in our first design.

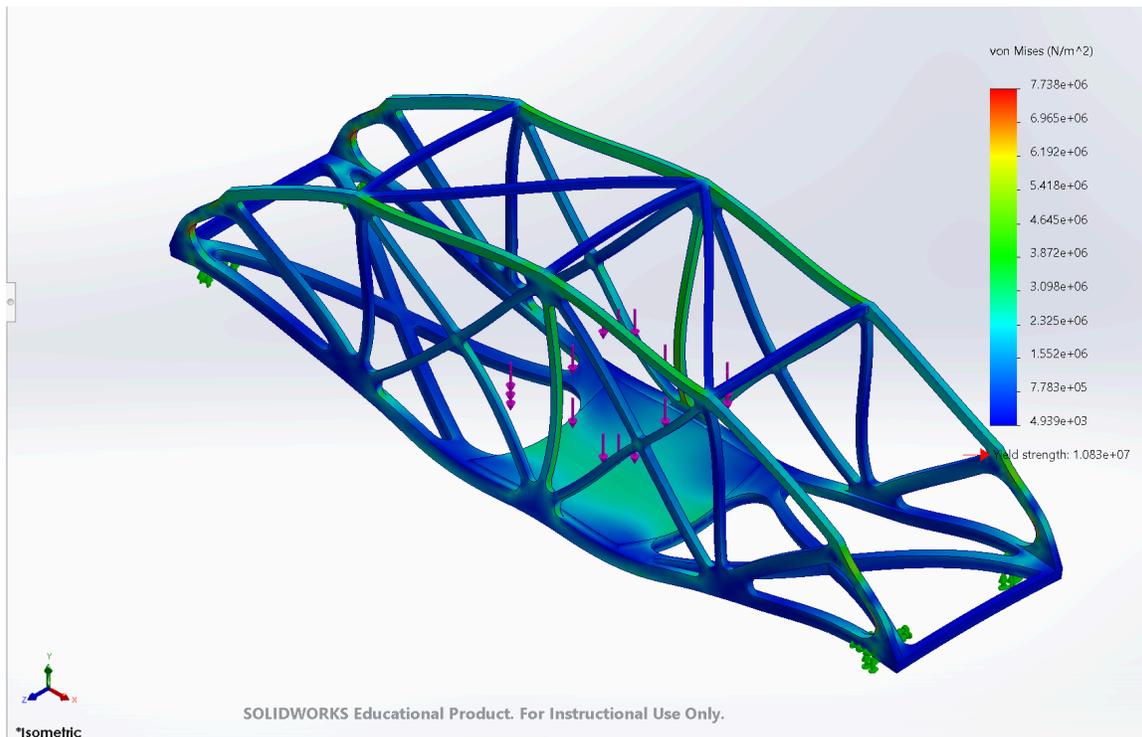
Figure 12. The Stress contour plot of our third design.

5. Displacement Results

Maximum Displacement (mm)	8.672

Table 15. The maximum displacement (mm) of our bridge. This is notably less than our first design.
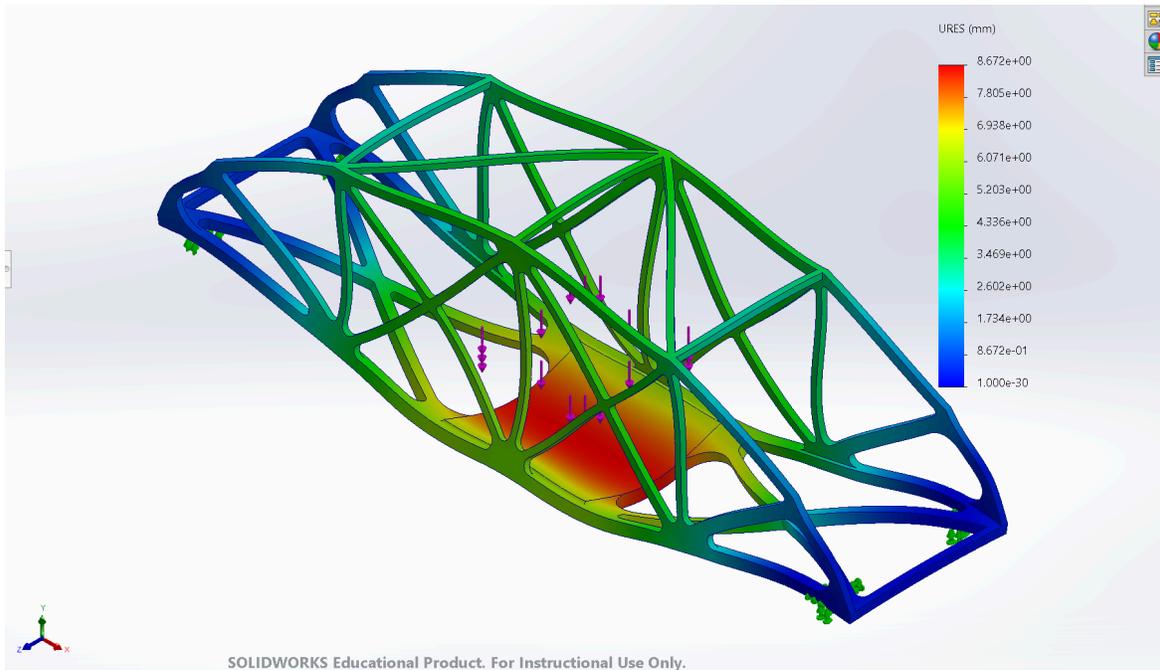
Figure 13. The displacement contour graph of our third design. Maximum displacement again occurs at the center plate.

6. Physical Test:

We got to choose one of these three iterations to be our test bridge. We chose to test our third design because it reduced the displacement on the center plate, which we feared would cause failure before stress. We wanted to test which point on this design would fail first and determine if failure due to buckling would occur before failure due to stress. Our bridge was then 3D-printed before recording its mass and being brought to failure using the bridge testing apparatus, recording the weight held (Table 16). The "Measured to Expected Bridge Mass Ratio" below (0.93) was the conversion factor used to calculate the adjusted mass in all tables.

Expected Bridge Mass (g)	40.0
Measured Bridge Mass (g)	37.2
Measured to Expected Bridge Mass Ratio	0.93

Weight held (N)	76.8
Bridge Weight to Weight Held Ratio	210.5

Table 16. The measured bridge mass, weight held (N), and the bridge mass to weight held ratio of the practice test were used in our third design.
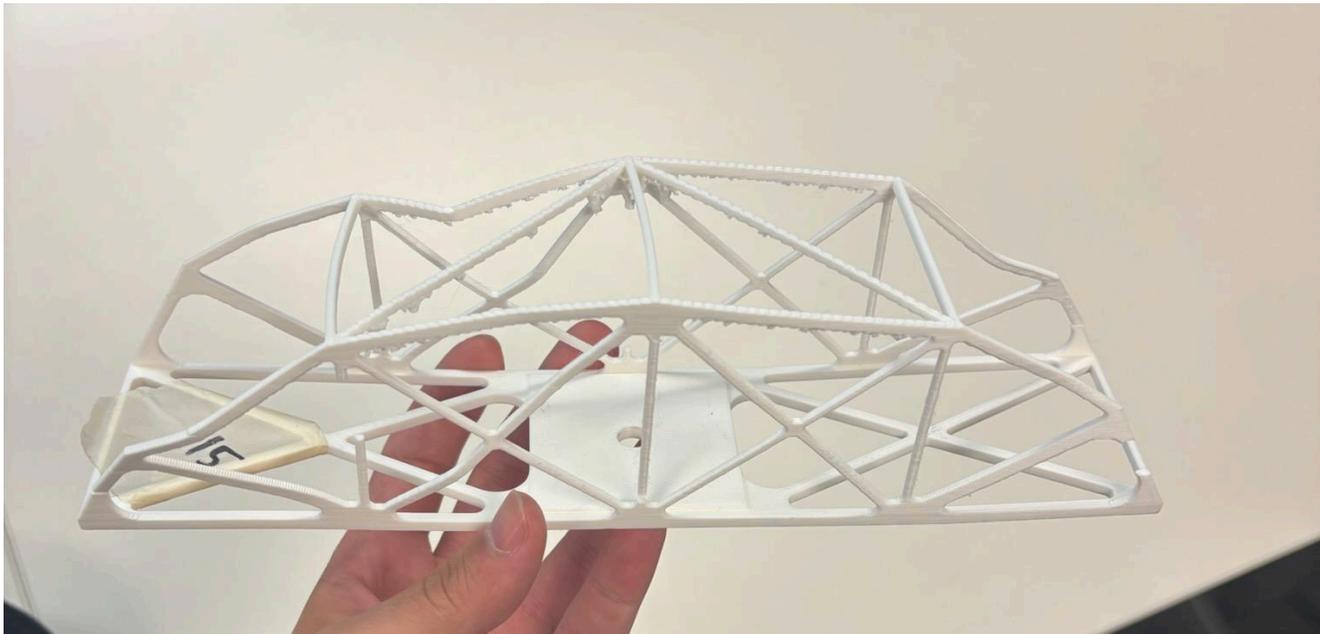
Figure 14. Displays an image of the bridge after the test. The bridge failed at its roof.

7. Discussion of Physical Test:

As seen in the above image, the bridge failed at the roof under approximately 77N of force (Figure 14). While this result is reasonable, the failure did not occur where we anticipated. Instead of the arches breaking at their base, as predicted by our model, the initial failure point was around the roof. We also determined that there wasn't a significant risk of our bridge failing from displacement due to our results. Moving forward, we must prioritize reinforcing the roof of our bridge, even if simulations do not highlight it as a critical failure point.

Furthermore, we discovered that the material was less dense than we initially expected. Our measured mass value was 93% of our predicted mass. Therefore, to meet the 40g mass requirement, our predicted mass can be as high as 43g.

Design #4

1. Introduction

In this iteration, we aimed to strengthen the bridge by removing some of the diagonal beams to reduce mass, allowing us to thicken the bridge, particularly at its roof.

2. Part Properties

Part Name	Design 4
Mass (g)	45.89
Adjusted Mass (g)	42.68
Volume (in³)	2.24
Surface area (in²)	56.55

Table 17. The part properties of our fourth design. The adjusted mass is slightly over 40g.

3. Study Properties

Mesh Density	Fine
Jacobian Points	16 Points
Degrees of Freedom	90,741
Number of Nodes	30,295
Number of Elements	14,617
Solve Type	Intel Sparse

Table 18. The study properties used to calculate the results for the FEA for our fourth design.

4. Stress Results

Max Von Mises Stresses (N/m²)	3.234e+06
Yield Strength (N/m²)	1.083e+07
Location of Max Von Mises	A little above the fillet between the arches and the base.
Factor of Safety at 50N load	3.349

Table 19. The results of the stress testing on our bridge. The max Von Mises forces were less than half of our previous designs under the same load.

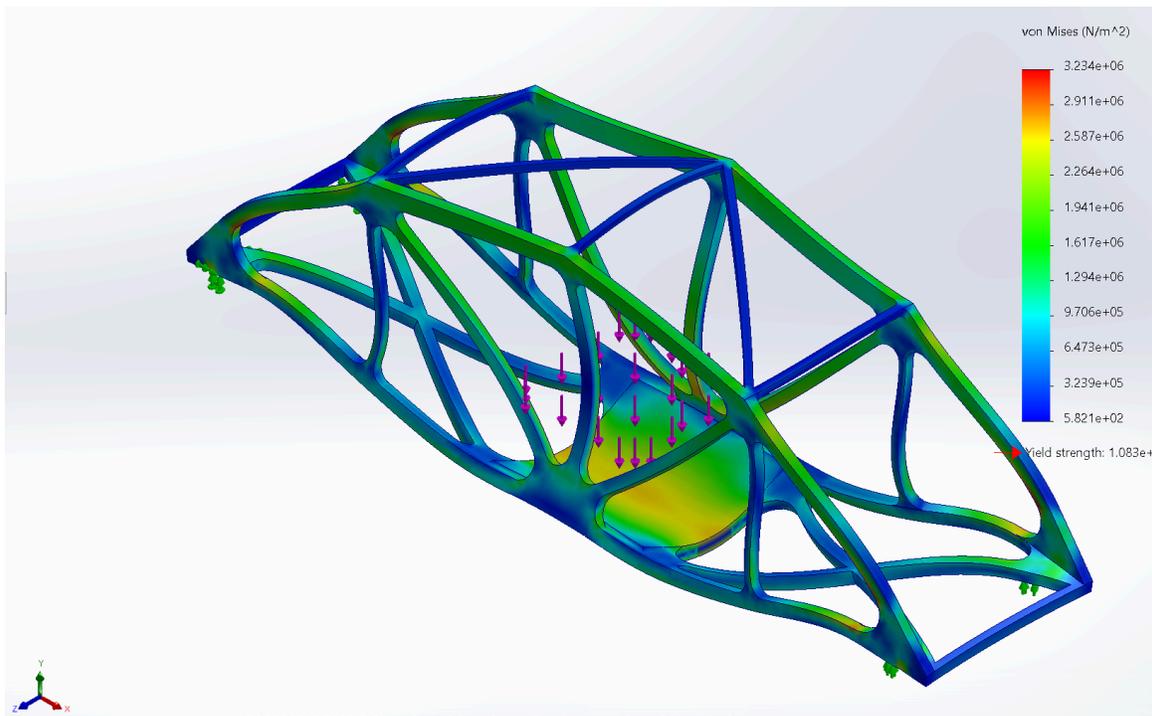**Figure 15.** The stress contour graph of our fourth design.

5. Displacement Results

Maximum Displacement (mm)	5.896

Table 20. The displacement was also much less.
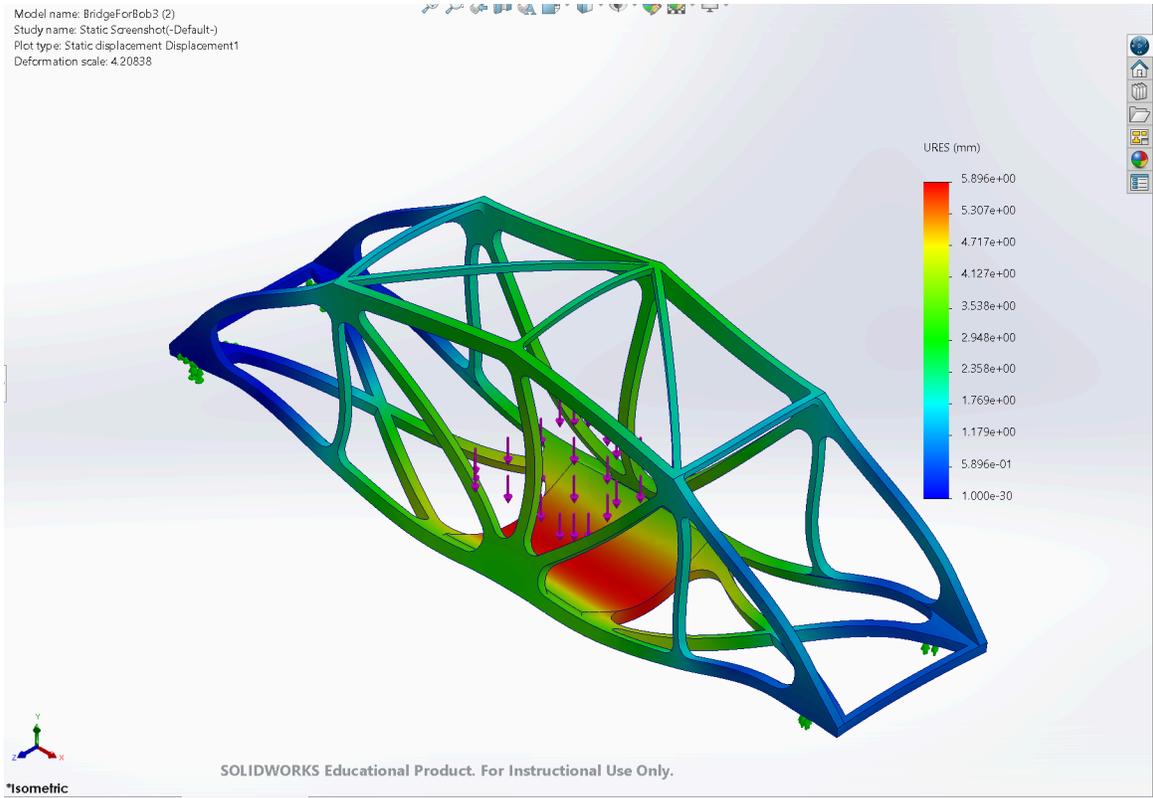
Figure 16. The displacement contour graph of our fourth design.

Design #5

1. Introduction

Our final design aimed to optimize force distribution and reduce weight by reducing beam thickness and incorporating additional supports. We added a central support for the center plate, reinforced critical failure points with fillets, and integrated a series of interconnected beams throughout the truss to improve overall strength.

2. Part Properties

Part Name	Design 3
Mass (g)	42.36
Adjusted Mass (g)	39.39
Volume (in^3)	2.07
Surface area (in^2)	61.54

Table 21. Displays the part properties of our fifth design. The adjusted mass was less than 40g!

3. Study Properties

Mesh Density	Fine
Jacobian Points	16 Points
Degrees of Freedom	108,147
Number of Nodes	36,079
Number of Elements	16,572
Solve Type	Intel Sparse

Table 22. The study properties used in our fifth design.

4. Stress Results

Max Von Mises Stresses (N/m²)	3.940e+06
Yield Strength (N/m²)	1.083e+07
Location of Max Von Mises	The base of the central vertical bars
Factor of Safety at 50N load	2.749

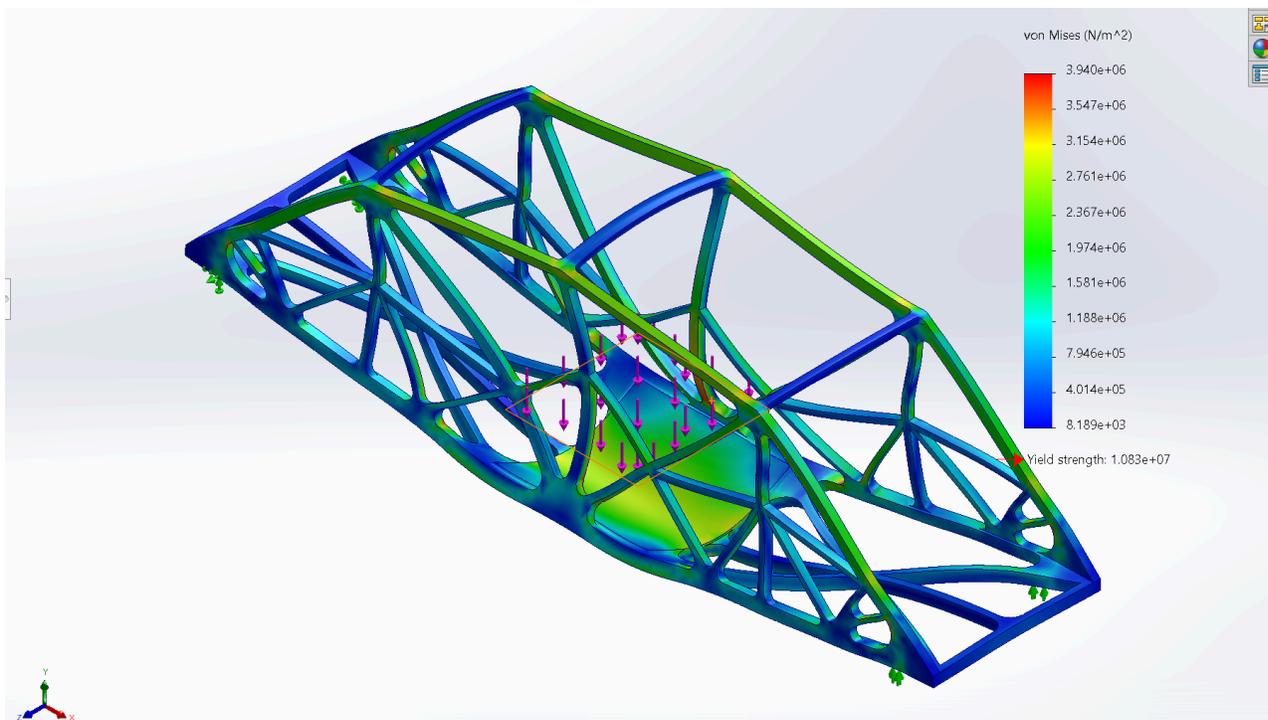**Table 23.** The stress results in our fifth design.

Figure 17. The stress contour graph. The maximum stress was at the base of the central vertical beams.

5. Displacement Results

Maximum Displacement (mm)	7.223

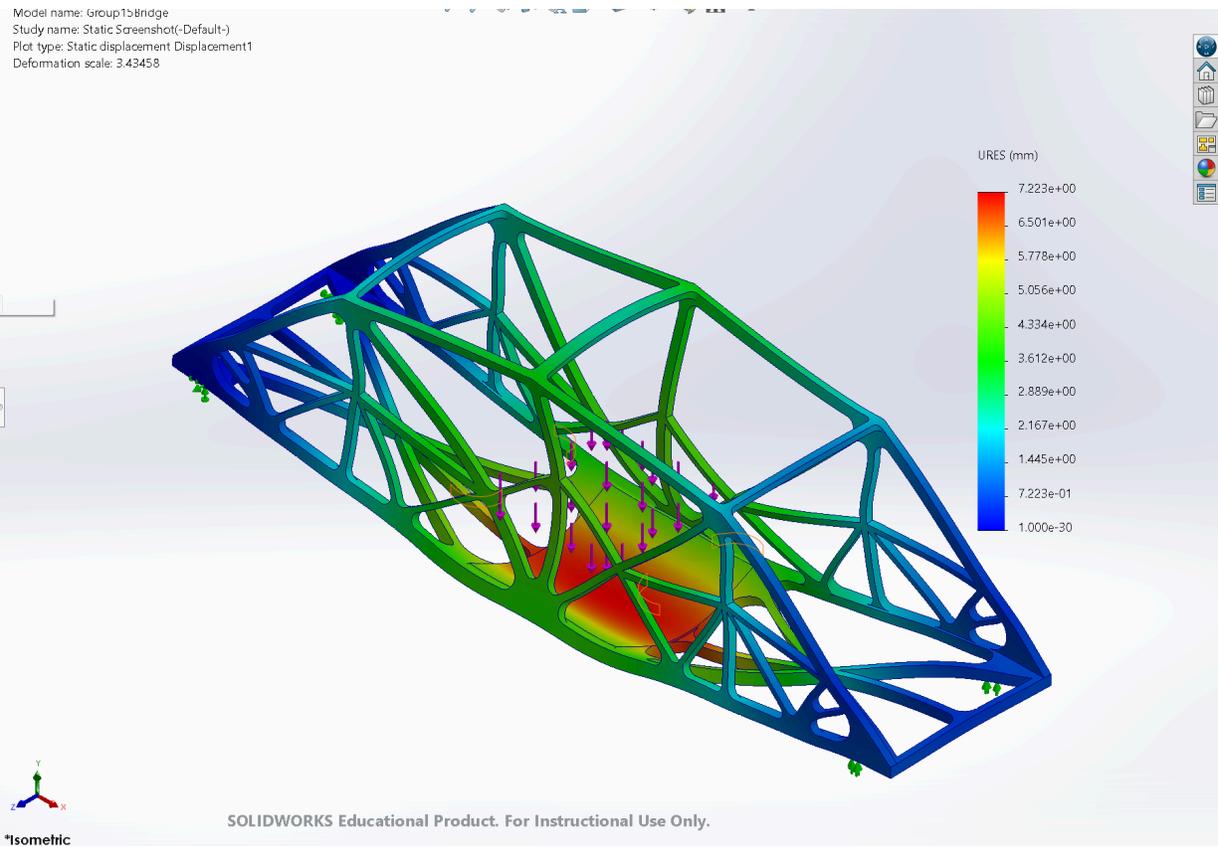**Table 24.** The maximum displacement of the model.

Figure 18. The displacement contour graph.

Final Design Selection

Using the results from our testing, we opted to use our fifth design because of its ability to minimize mass while distributing forces to reduce stress. Even though our fourth design had a lower maximum Von Mises stresses (Table 19; $3.234e+06 \text{N/m}^2$) than our fifth (Table 23; $3.940e+06 \text{N/m}^2$) , at higher forces (above 100 Newtons), we noticed the two bridges slowly equalizing in performance. Additionally, the fourth bridge had a greater mass than our final design (Tables 17 and 21; 45.89g vs. 42.36g). Using the conversion factor from the predicted mass to the actual mass determined in our physical test (0.93), the fifth bridge's mass actually falls under the 40g mass ceiling (39.39g) while our fourth design would have exceeded the mass restriction by 2.5g. The fifth design was simply more attractive since the penalty for being overweight increases proportionally to the square of the ratio of 40g to your weight:

$$\text{Weight (official)} = \text{Weight (actual)} \times (40 \text{ g} / \text{Bridge weight})^2$$

Due to the combination of similar performances at greater loads and the strict penalties for being overweight, our group decided to use our fifth bridge design for final testing over our slightly stronger fourth bridge design.

Prediction of Final Weight

In order to predict the failure point of our bridge, we performed a series of tests, increasing the applied force by 5N each iteration until we reached the yield bridge's yield strength ($1.083e+07N/m^2$). We recorded and plotted this data in the graph below. Setting the equation of the generated line of best fit (y=78744*x + 5405) to the yield strength, we calculated the expected failure point to occur at **137N**.
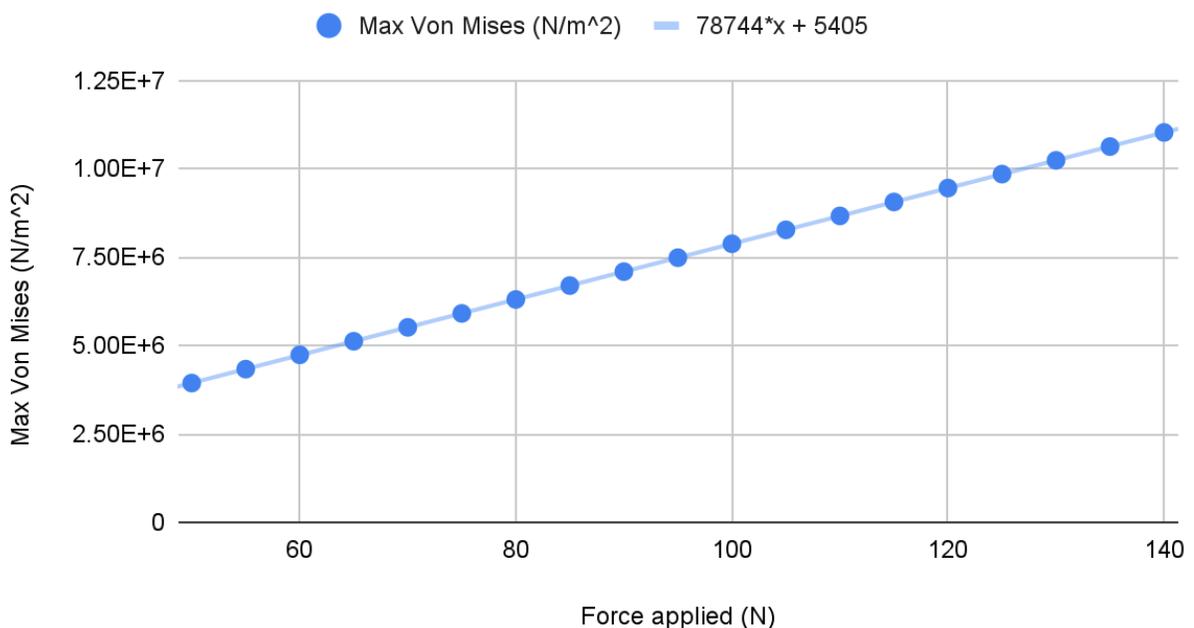

Figure 19. Displays the Max Von Mises forces (N/m^2) vs. force applied (N). Data points were taken by increasing the force applied by 5N. It is a linear trend, so the failure point could be calculated with relative certainty.

Results

Group	Test #	Bridge mass (g)	Weight held (kgf)	Weight ratio (just FYI, not part of contest rules)	Weight held, including penalty according to contest rules (kgf)	Performance score (see contest rules)	Rank
1	1	41.7	36.3	870.5	33.4	97	2
	2	41.4	38.1	920.3	35.6	100	1
2	1	45.6	32.8	719.3	25.2	85	3
	2	47.5	34.2	720.0	24.3	84	5
3	1	40.5	11.1	274.1	10.8	65	25
	2	41.4	11.1	268.1	10.4	65	27
4	1	41.1	13.0	316.3	12.3	67	22
	2	40.3	11.1	275.4	10.9	65	24
5	1	37.4	14.6	390.4	14.6	71	15
	2	35.8	13.5	377.1	13.5	69	20
6	1	36.8	17.7	481.0	17.7	75	11
	2	35.8	16.8	469.3	16.8	74	12
7	1	39.7	13.6	342.6	13.6	69	18
	2	39.9	13.5	338.3	13.5	69	20
8	1	38.2	21.3	557.6	21.3	80	8
	2	37.7	23.2	615.4	23.2	83	6
9	1	40.5	16.0	395.1	15.6	72	14
	2	40.0	15.7	392.5	15.7	72	13
10	1	37.1	5.7	153.6	5.7	58	31
	2	36.6	5.2	142.1	5.2	57	32
11	1	38.4	12.0	312.5	12.0	67	23
	2	38.1	13.6	357.0	13.6	69	18
12	1	40.6	25.6	630.5	24.8	85	4
	2	40.7	23.3	572.5	22.5	82	7
13	1	37.0	20.9	564.9	20.9	79	9
	2	36.5	20.4	558.9	20.4	79	10
14	1	41.1	8.3	201.9	7.9	61	30
	2	40.3	8.2	203.5	8.1	61	29
15	1	39.5	10.6	268.4	10.6	65	26
	2	39.3	10.2	259.5	10.2	64	28
16	1	36.2	3.8	105.0	3.8	55	34
	2	36.7	4.3	117.2	4.3	56	33
17	1	43.2	16.9	391.2	14.5	70	16
	2	41.6	15.6	375.0	14.4	70	17

Figure 20. Table of Results from Official Bridge Testing

Test	Expected bridge mass (g)	Measured bridge mass (g)	Expected weight held (N)	Actual weight held (N)
1	39.39	39.5	137	104.0
2		39.3		100.1

Table 25. Processed data from Official Bridge Testing.
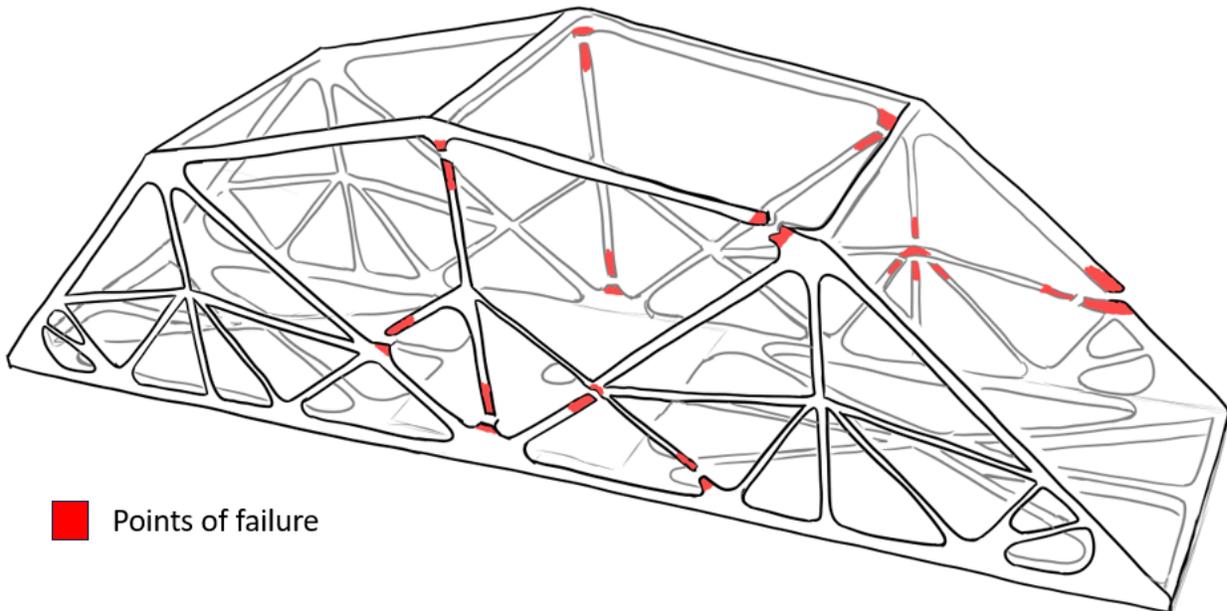

Points of failure

Figure 21. Diagram of the final bridge after testing and the different points where it failed.

Analysis of the results

When looking at the data table, and the diagram above (Figure 21) to the projected stress and displacement models of the final bridge (Figures 17 & 18) there are significant discrepancies.

Firstly, and most notably, the actual supported weight (N) is significantly lower than the predicted weight, with a factor of 0.76 for the first test and 0.73 for the second test. Since we utilized the FEA multiple times, and we were told it had a high accuracy, we were quite surprised by these results. It could have been dependent on print inaccuracies or a weaker than expected material. The print inaccuracies are evidenced by the mass difference between the two final bridge prints.

Secondly, the simulation did not accurately predict the location that the bridge would fail at, with the exception of the base of the vertical beams. However, the base of the vertical central beams did not break first. Surprisingly, our bridge first failed at the intersections of the diagonal supports. The simulations predicted these locations to have considerably lower stress values than the joints at the top of the

bridge and the base of the central supports. These significant differences in yield location are likely the cause of the significant difference between our expected and actual results.

Our two test bridges weighed 39.5g and 39.3g, respectively, below the maximum weight allowed. Our first tested bridge successfully withstood a maximum load of 10.6 kilograms-force(kgf) before critical failure. Our second attempt failed at a lesser 10.2kgf, likely due to the slightly smaller mass. Both bridges ended up failing through stress at lower kgf than expected as we either exceeded the PLA's tensile or shear strength limit.

We also noticed that the base of our bridge experienced less deformation than expected. The displacement model predicted the bottom of our bridge to move over 7mm, but we could not see any deformation during the live tests. While it is possible that we missed the small deformation, it is far more likely that the steel plate prevented the bridge underneath it from deforming. Additionally, the diagonal supports on our bridge experienced more deformation than expected. It can therefore be assumed that the more rigid base skewed our results by transferring the load it would have borne through displacement to other parts of the bridge.

Most surprising of all, our bridges saw a mild increase in maximum strength after an initial failure. While we do not understand exactly how or why this occurred, we can assume that the mild deformation and stress release from initial break mildly increased the bridges overall strength by better dispersing the load.

While both of our final bridge prints did not perform as well as we predicted, they still taught us valuable lessons on material strength. We saw the disparities between real practice and simulations, highlighting the potential shortcomings of FEA, while displaying its numerous highly useful applications.

What We Would Do Differently

Looking back at our final bridge design, we would make multiple changes that would hopefully improve the maximum weight our bridge could hold. We made these realizations through the testing of our two final bridge prints and the success of other groups.

The first change we needed to make was prioritizing stress over displacement. Throughout the entire design process we placed equal weight on maintaining a minimal displacement and ensuring that the Von Mises Stress was minimized whenever possible. Our group was alarmed when SolidWorks required a large displacement model to run our simulations, so we made changes to our bridges to keep the simulations within the standard settings. However, both prints of our final bridge ended up failing in stress at the points outlined by the simulation longer before the bridge would have failed in displacement. In fact, the bridge hardly moved during testing before the outermost supporting beams snapped from the Von Mises Stress. Through the testing of our bridge and conversations with more successful teams that ignored displacement entirely, we realized that we significantly reduced our bridge's maximum load by minimizing displacement instead of stress.

We should have also explored arch bridges in far more depth. We noticed at least one other experience of a successful trial during the testing date with an arch bridge, and we realized our missed opportunity. While we did consider testing and implementing arch bridge designs, we encountered early weight problems and ended up scrapping the designs. However, these issues were primarily a result of an overly ambitious base rather than the arch itself. Had we compared the arch bridge to our standard truss alternatives, we would have made a more informed decision for our final bridge design. Even if we ended up staying with the standard truss, the comparison could have revealed weaknesses in our current design and allowed us to optimize our bridge for the final submission.

We would also make a considerably larger central hole if we could redo the project. On the testing day, we realized that the 1.75" by 1.75" steel plate on top of the

bridge significantly strengthened the central area. If we reduced the fill of the area underneath the plate marginally, we could free up more mass. This newfound material would be used to increase fillet size in high-stress points throughout the bridge, particularly on the outermost supports. While such a change does have the potential to result in the center of our bridge breaking through, it would be far more likely to increase our maximum load.

We would also slightly reduce the thickness of our bridge's base. Compared to many of our more successful competitors, our base, and particularly the base where the steel plate was applied, was noticeably thicker. Since we did not notice any of the bridges failing from displacement, we are confident that a marginal decrease in thickness would not have a significant impact on bridge strength. We could then repurpose the saved material to add support to high-stress areas. We would hope to be able to increase the width of the outermost support beams of our bridge as well as the diagonal side trusses as these were the two areas that failed during the final test.

Finally, we would ensure that all of our joints were filleted. From our results, it appears that the FEA cannot accurately predict the failure of unfilleted joints as our bridge failed at these points before the expected locations. Filleting every connection should have a noticeable impact on our maximum strength.

By effectively ignoring displacements, just like some of the most successful groups, spending more time experimenting with different bridge models, and filleting each connection, we could have significantly increased our maximum load. Additionally, the thinning of our bridge's base and reduction of the supports underneath the load plate would have freed up a substantial amount of mass that we could have used to further reduce stress. The combination of these alterations, alongside the printing of additional bridges to confirm our preliminary results, as the simulations did not necessarily agree with the live tests, would have produced a considerably stronger final bridge. This final bridge would either resemble our final truss bridge or have an arch shape

Communication

The majority of meetings were held virtually since the designs and evaluations were carried out using SolidWorks.

- November 19 - First Meeting

This was the only formal meeting where we met in person. The meeting took place at Salvatori Computer Science Center (SAL). During this meeting, we reviewed the bridge iterations designed prior to the meeting, as agreed upon according to the specifications and general style we wanted to follow. After the meeting, we were able to conclude with 2 valid designs, though they would need further analysis before selecting one for the first testing. Therefore, the following objective was established for the next meeting: to begin performing Finite Element Analysis and refining both iterations according to our interests.

- November 21 - Second Meeting

As agreed, this virtual meeting focused on performing the Finite Element Analysis (FEA) of the first two designs. Additionally, after the analysis, a new design was proposed, the third, which was based on the second but with a series of changes that we deemed beneficial after the simulations. In this meeting, the FEA of this latest design was also carried out, which was selected to serve as our test bridge because it reduced the displacement on the center plate. Predictions were also made prior to testing. Thus, the next step would be to evaluate the results obtained from this first test.

- November 29 - Third Meeting

This third meeting was also held virtually. During the meeting, the results of the first testing were reviewed, where we presented the third design. Since we still did not have the bridge after testing, we could only analyze the weight supported by the bridge, which we concluded was reasonable. However, it was necessary to identify where the bridge had failed in order to strengthen those areas in the next design. Thus, the objective for the following meeting would be to evaluate the bridge after being tested.

- December 3 - Fourth Meeting

Although the tested bridge was collected collectively, this meeting once again took place virtually. During the meeting, we observed where the bridge had failed, and it did not align with the points predicted by the simulations. Additionally, it was noted that the material density was lower than expected, allowing for a bridge design with a higher predicted mass. Therefore, in this meeting, the necessary changes were made, resulting in the fourth design. The FEA of this design was also carried out. This latest design was heavier than desired, and therefore, it was not satisfactory to be used as the final design for the competition day. The objective of the next meeting would be to optimize the design to achieve a new bridge that reduces weight and optimizes the force distribution.

- December 4 - Fifth Meeting

This was the final meeting before the competition day, with the goal of achieving a final design with reduced weight and optimized force distribution. Thus, the final design was developed for 3D printing. Changes were made to the thickness, allowing for weight reduction, and additional supports, fillets, and interconnected beams were added to improve the bridge's strength, thereby increasing the weight it could support. The corresponding FEA was conducted, and it was concluded to be satisfactory for presentation for printing.

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